Measurement of the CKM angle γ at LHCb

Agnieszka Dziurda
on behalf of the LHCb collaboration

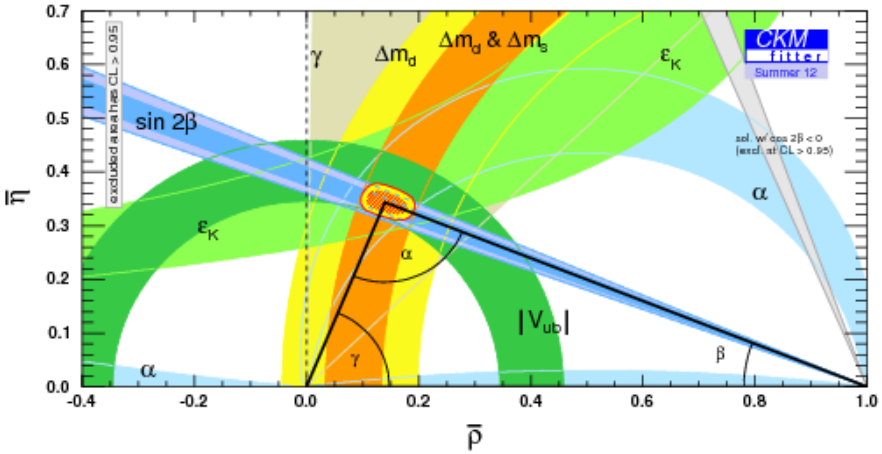
Henryk Niewodniczanski Institute of Nuclear Physics PAS, Cracow

January 9, 2013

Motivation: CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



- Amplitudes of weak interactions depend on 4 parameters in the CKM matrix.
- One goal in flavor physics is to thoroughly test whether these 4 parameters really do describe both the magnitudes and phases of quark transitions associated with many decay processes
- The weak phase $\gamma \propto Arg(V_{ub})$ is the least well measured of the CKM angles
- Any discrepancy in the position of the apex of the Unitarity Triangle from the different measurements would indicate physics beyond Standard Model.

Motivation: γ angle

Possibilities of measurement γ angle from B decays mediated only by:

- tree-level transitions which are benchmark for the SM $\rightarrow$ today
- loop-level transitions which can indicate New Physics contribution

Measurement using tree-level decays:

- time-integrated methods using
  $B \rightarrow DK$, $B \rightarrow DK^*$, $B \rightarrow D^*K$, $B \rightarrow DK\pi\pi$, also $B \rightarrow D\pi$
- time-dependent methods using
  $B_s \rightarrow D_sK$, $B_s \rightarrow D_sK\pi\pi$

LHCb performed γ combination using time-integrated methods for $B \rightarrow DK$ and $B \rightarrow D\pi$ decays to D final states:

- two-body: $D^0 \rightarrow K\pi$, KK,$\pi\pi$ (Phys. Lett. B 712 (2012) 203)
- three-body: $D^0 \rightarrow K_shh$ (Phys. Lett. B 718 (2012) 43)
- four-body: $D^0 \rightarrow K\pi\pi\pi$ (LHCb-CONF-2012-030)

The analyses are based on pp collision data sample of 1 fb^{-1} collected at LHC in 2011 at the center-of-mass energy $\sqrt{s} = 7\,TeV$.

Motivation: γ angle

Possibilities of measurement γ angle from B decays mediated only by:

- tree-level transitions which are benchmark for the SM $\rightarrow$ today
- loop-level transitions which can indicate New Physics contribution

Measurement using tree-level decays:

- time-integrated methods using
  $B \rightarrow DK$, $B \rightarrow DK^*$, $B \rightarrow D^*K$, $B \rightarrow DK\pi\pi$, also $B \rightarrow D\pi$
- time-dependent methods using
  $B_s \rightarrow D_sK$, $B_s \rightarrow D_sK\pi\pi$

LHCb performed γ combination using time-integrated methods for $B \rightarrow DK$ and $B \rightarrow D\pi$ decays to D final states:

- two-body: $D^0 \rightarrow K\pi$, KK,$\pi\pi$ (Phys. Lett. B 712 (2012) 203)
- three-body: $D^0 \rightarrow K_shh$ (Phys. Lett. B 718 (2012) 43)
- four-body: $D^0 \rightarrow K\pi\pi\pi$ (LHCb-CONF-2012-030)

The analyses are based on pp collision data sample of 1 fb^{-1} collected at LHC in 2011 at the center-of-mass energy $\sqrt{s} = 7\,TeV$.

Motivation: γ angle

Possibilities of measurement γ angle from B decays mediated only by:

- tree-level transitions which are benchmark for the SM $\rightarrow$ today
- loop-level transitions which can indicate New Physics contribution

Measurement using tree-level decays:

- time-integrated methods using
  $B \rightarrow DK$, $B \rightarrow DK^*$, $B \rightarrow D^*K$, $B \rightarrow DK\pi\pi$, also $B \rightarrow D\pi$
- time-dependent methods using
  $B_s \rightarrow D_sK$, $B_s \rightarrow D_sK\pi\pi$

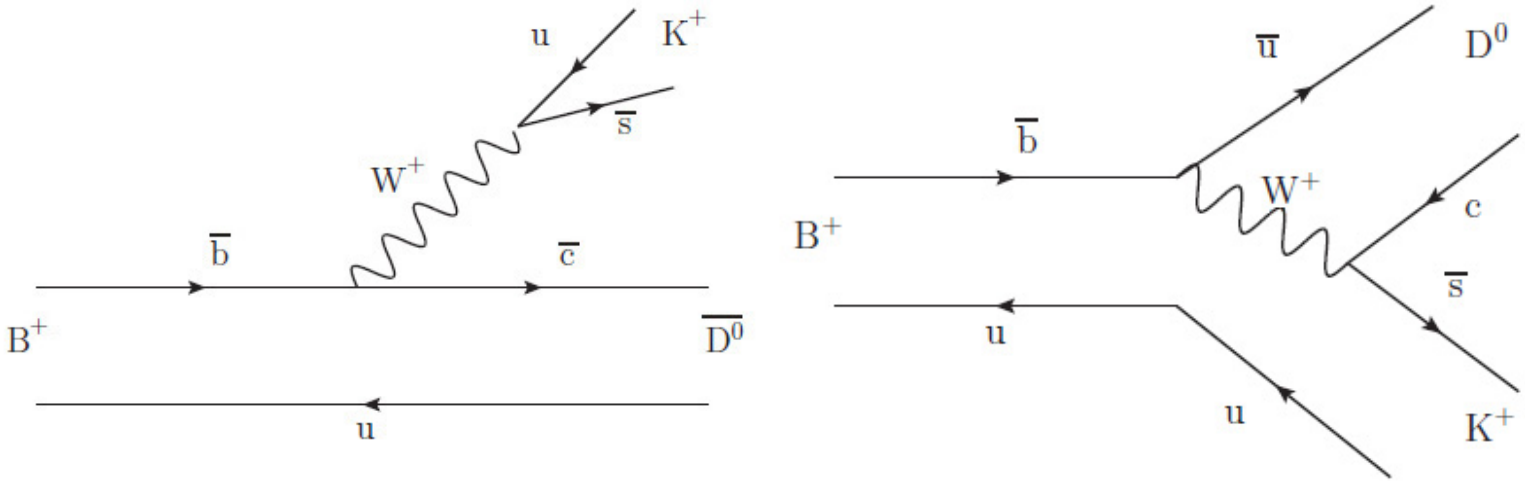
LHCb performed γ combination using time-integrated methods for $B \rightarrow DK$ and $B \rightarrow D\pi$ decays to D final states:

- two-body: $D^0 \rightarrow K\pi$, KK,$\pi\pi$ (Phys. Lett. B 712 (2012) 203)
- three-body: $D^0 \rightarrow K_shh$ (Phys. Lett. B 718 (2012) 43)
- four-body: $D^0 \rightarrow K\pi\pi\pi$ (LHCb-CONF-2012-030)

The analyses are based on pp collision data sample of 1 fb^{-1} collected at LHC in 2011 at the center-of-mass energy $\sqrt{s} = 7\,TeV$.

Time-integrated methods

- Sensitivity to γ from interference between $b \to c$ and $b \to u$ transitions at tree level, when D final state is accessible to both D^0 and $\bar{D}^0$
- Aside from γ, have hadronic unknowns $r_{B(D)}$, $\delta_{B(D)}$, where ratio of favored to suppressed $B(D)$ decay amplitudes is $r_B e^{i(\delta_B - \gamma)}$ $(r_D e^{i\delta_D})$
- Relationship between γ and physical observables are related to the D final state.



Gronau-London-Wyler (GLW) method

- $D \to$ CP-eigenstate, e.g. $\pi\pi$, KK
- Observables: the partial rate R_{CP+} and the asymmetry A_{CP+}:

$$R_{CP+} = 2\frac{\Gamma(B^- \to D_{CP+}K^-)+\Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D^0K^-)+\Gamma(B^+ \to \bar{D}^0K^+)} = 1 + r_B^2 + 2r_B cos(\delta_B)cos(\gamma)$$

$$A_{CP+} = \frac{\Gamma(B^- \to D_{CP+}K^-)-\Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D_{CP+}K^-)+\Gamma(B^+ \to D_{CP+}K^+)} = \frac{2r_B sin(\delta_B)sin(\gamma)}{R_{CP+}}$$

- The equivalents also exist for $B \to D\pi$, but the asymmetry is expected to be small.

Atwood-Dunietz-Soni (ADS) method

- $D \to$ quasi-flavour-specific state e.g. $K\pi$, $K\pi\pi\pi$
- The main observables are related to the doubly-Cabibbo-suppressed D final state:

$$R_{ADS} = \frac{\Gamma(B^- \to (K^+\pi^-)K^-)+\Gamma(B^+ \to (K^-\pi^+)K^+)}{\Gamma(B^- \to (K^-\pi^+)K^-)+\Gamma(B^+ \to (K^+\pi^-)K^+)} = r_B^2 + r_D^2 + 2r_B r_D C_f cos(\delta_B + \delta_D)cos(\gamma)$$

$$A_{ADS} = \frac{\Gamma(B^- \to (K^+\pi^-)K^-)-\Gamma(B^+ \to (K^-\pi^+)K^+)}{\Gamma(B^- \to (K^+\pi^-)K^-)+\Gamma(B^+ \to (K^-\pi^+)K^+)} = \frac{2r_B r_D C_f sin(\delta_B+\delta_D)sin(\gamma)}{R_{ADS}}$$

- C_f is the coherence factor, with $C_f = 1$ for $K\pi$ and $0 < C_f < 1$ for $K\pi\pi\pi$

Gronau-London-Wyler (GLW) method

- $D \to$ CP-eigenstate, e.g. $\pi\pi$, KK
- Observables: the partial rate R_{CP+} and the asymmetry A_{CP+}:

$$R_{CP+} = 2\frac{\Gamma(B^- \to D_{CP+}K^-)+\Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D^0K^-)+\Gamma(B^+ \to \bar{D}^0K^+)} = 1 + r_B^2 + 2r_B cos(\delta_B)cos(\gamma)$$

$$A_{CP+} = \frac{\Gamma(B^- \to D_{CP+}K^-)-\Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D_{CP+}K^-)+\Gamma(B^+ \to D_{CP+}K^+)} = \frac{2r_B sin(\delta_B)sin(\gamma)}{R_{CP+}}$$

- The equivalents also exist for $B \to D\pi$, but the asymmetry is expected to be small.

Atwood-Dunietz-Soni (ADS) method

- $D \to$ quasi-flavour-specific state e.g. $K\pi$, $K\pi\pi\pi$
- The main observables are related to the doubly-Cabibbo-suppressed D final state:

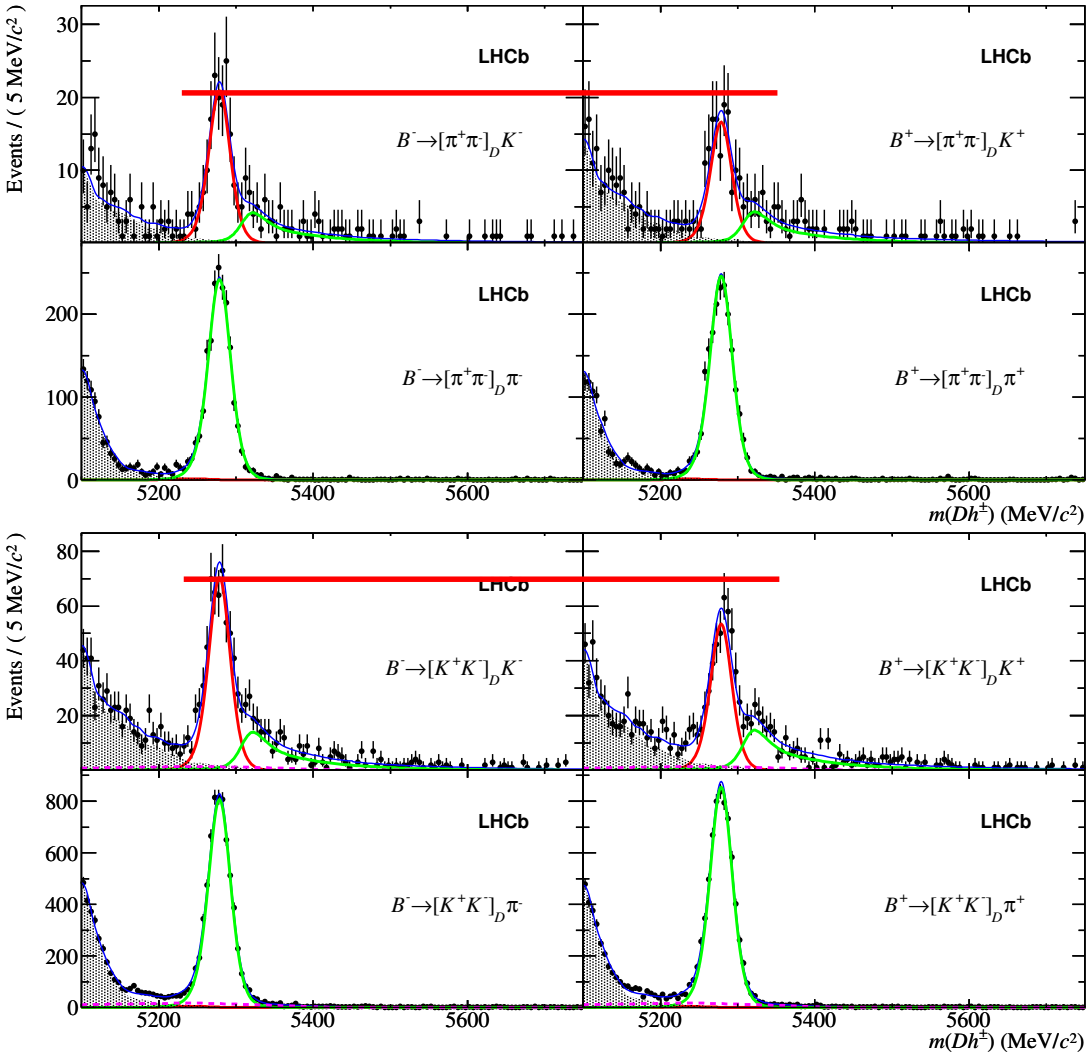
$$R_{ADS} = \frac{\Gamma(B^- \to (K^+\pi^-)K^-)+\Gamma(B^+ \to (K^-\pi^+)K^+)}{\Gamma(B^- \to (K^-\pi^+)K^-)+\Gamma(B^+ \to (K^+\pi^-)K^+)} = r_B^2 + r_D^2 + 2r_B r_D C_f cos(\delta_B + \delta_D)cos(\gamma)$$

$$A_{ADS} = \frac{\Gamma(B^- \to (K^+\pi^-)K^-)-\Gamma(B^+ \to (K^-\pi^+)K^+)}{\Gamma(B^- \to (K^+\pi^-)K^-)+\Gamma(B^+ \to (K^-\pi^+)K^+)} = \frac{2r_B r_D C_f sin(\delta_B+\delta_D)sin(\gamma)}{R_{ADS}}$$

- C_f is the coherence factor, with $C_f = 1$ for $K\pi$ and $0 < C_f < 1$ for $K\pi\pi\pi$

GLW results

Phys. Lett. B 712 (2012) 203



Asymmetries are visible in the suppressed DK modes

$$A_{KK} = 0.148 \pm 0.037 \pm 0.010$$
$$A_{\pi\pi} = 0.135 \pm 0.066 \pm 0.010$$

in average:

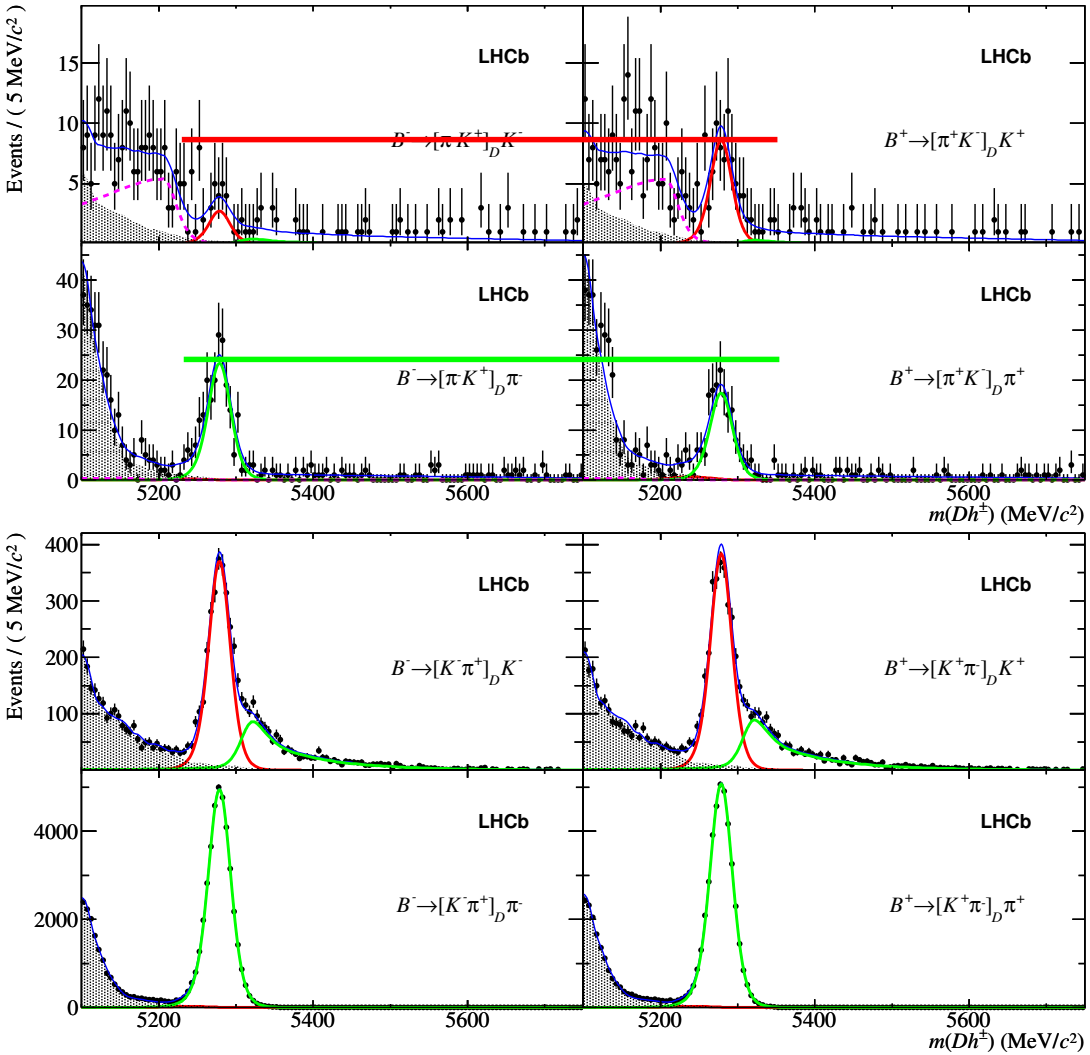
$$A_{CP+} = 0.145 \pm 0.032 \pm 0.010$$

and partial rate:

$$R_{CP+} = 1.007 \pm 0.038 \pm 0.012$$

ADS results: $D \to K\pi$

Phys. Lett. B 712 (2012) 203



Asymmetries are visible in both suppressed D modes

$$A_{ADS(\pi)} = 0.143 \pm 0.062 \pm 0.011$$
$$R_{ADS(\pi)} = 0.00410 \pm 0.00025 \pm 0.00005$$

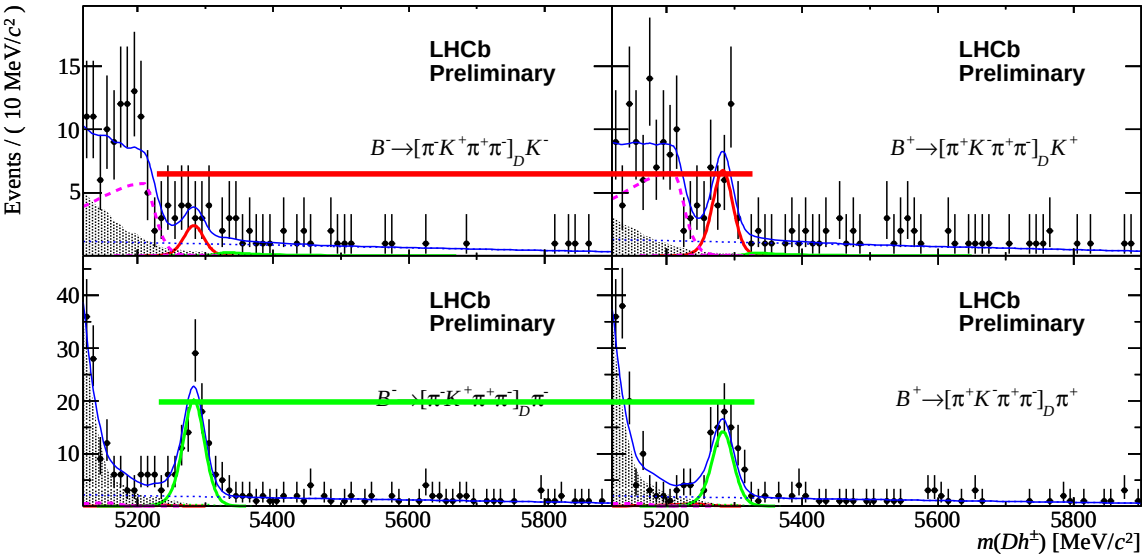
$$A_{ADS(K)} = -0.52 \pm 0.15 \pm 0.02$$
$$R_{ADS(K)} = 0.0152 \pm 0.0020 \pm 0.0004$$

Considering KK, $K\pi$ and $\pi\pi$ together, CPV is observed (5.8σ) in $B \to DK$ decays for the first time.

ADS results: $D \to K\pi\pi\pi$

LHCb-CONF-2012-030

- Compared to $B \to D(K\pi)K$:
  r_B and δ_B are unchanged
  the D decay parameters are different.
- First observations of the 4-body ADS modes in both
  $B \to D\pi$ ($> 10\sigma$)
  $B \to DK$ (5.1σ)
- Visible asymmetries in both $B \to D\pi$ and $B \to DK$



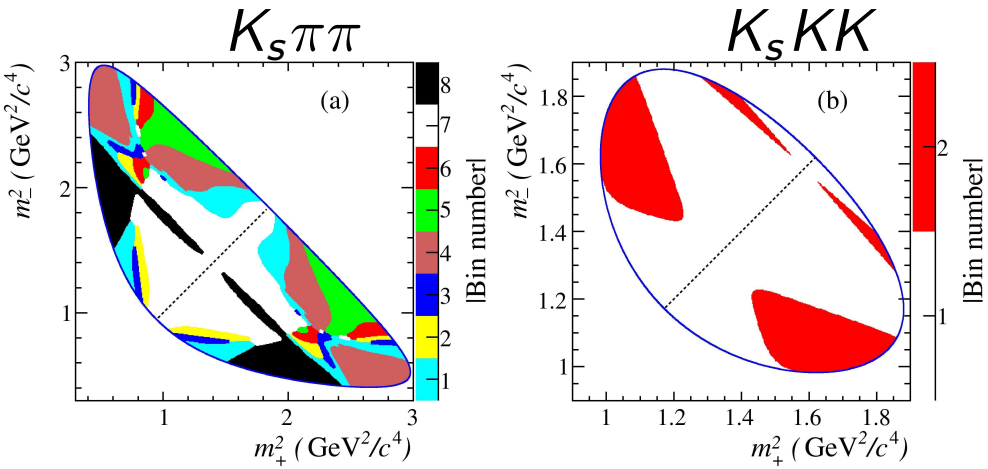
$$A^{K3\pi}_{ADS(K)} = -0.42 \pm 0.22$$
$$R^{K3\pi}_{ADS(K)} = 0.0124 \pm 0.0027$$

$$A^{K3\pi}_{ADS(\pi)} = +0.13 \pm 0.10$$
$$R^{K3\pi}_{ADS(\pi)} = 0.00369 \pm 0.00036$$

Giri-Grossman-Soffer-Zupan (GGSZ) method

It is possible to measure γ by comparing Dalitz plots of $D \to K_S\pi\pi$ (or K_SKK) decay for $B^+ \to DK^+$ and $B^- \to DK^-$

Current LHCb analysis uses CLEO-c measurements of the strong phase variation as input
(Phys. Rev. D 82 (2010) 112006)
Dalitz plots are binned in regions of similar strong phase.



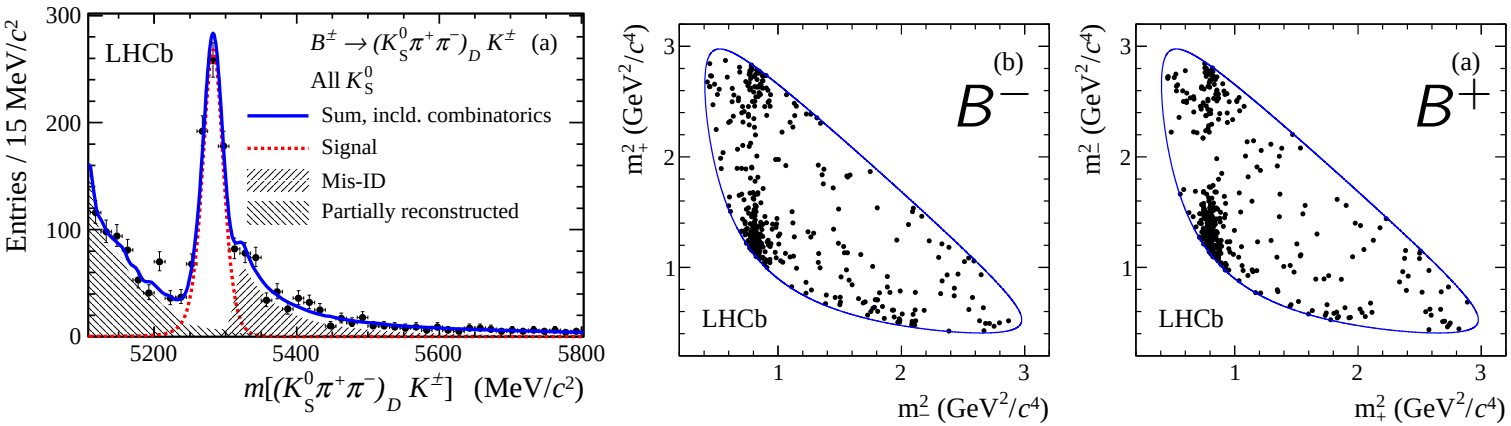
The population in *ith* bin is given by:

$$N^+_{\pm i} = h_{B^+}\left[K_{\mp i} + (x_+^2 + y_+^2)K_{\pm i} + 2\sqrt{K_iK_{-i}}(x_+c_{\pm i} \mp y_+s_{\pm i})\right],$$
$$N^-_{\pm i} = h_{B^-}\left[K_{\pm i} + (x_-^2 + y_-^2)K_{\mp i} + 2\sqrt{K_iK_{-i}}(x_-c_{\pm i} \pm y_-s_{\pm i})\right]$$

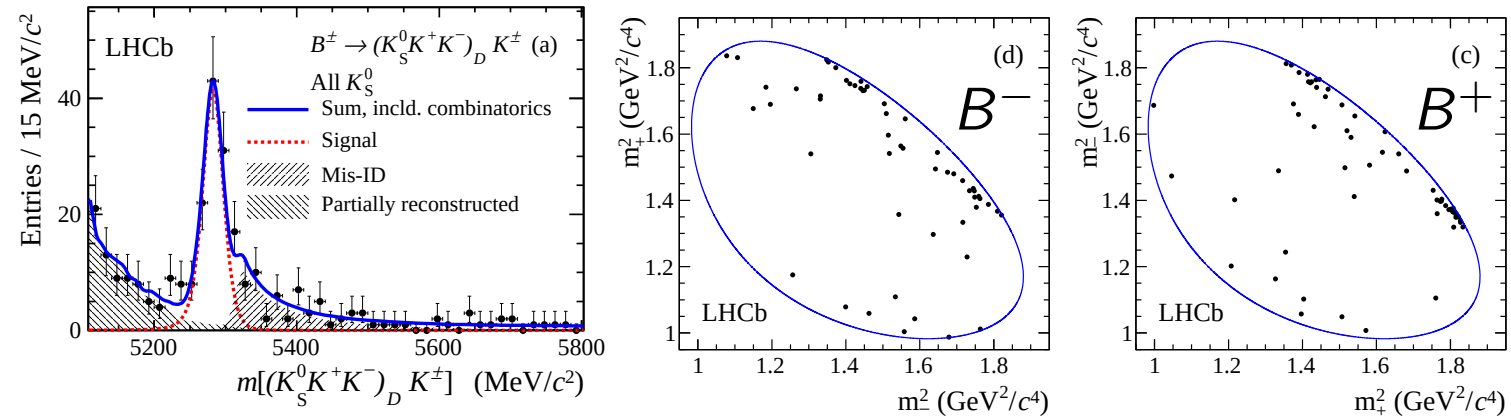
K_i is the number of events in bin of flavour-tagged D decays
c_i (s_i) is cos(sin) of strong phase difference in each bin (taken from CLEO-c)
$x_\pm = r_B\cos(\delta_B \pm \gamma)$ and $y_\pm = r_B\sin(\delta_B \pm \gamma)$
r_B and δ_B are unchanged

GGSZ results

Phys. Lett. B 718 (2012) 43



$D \to K_s\pi\pi$ final state

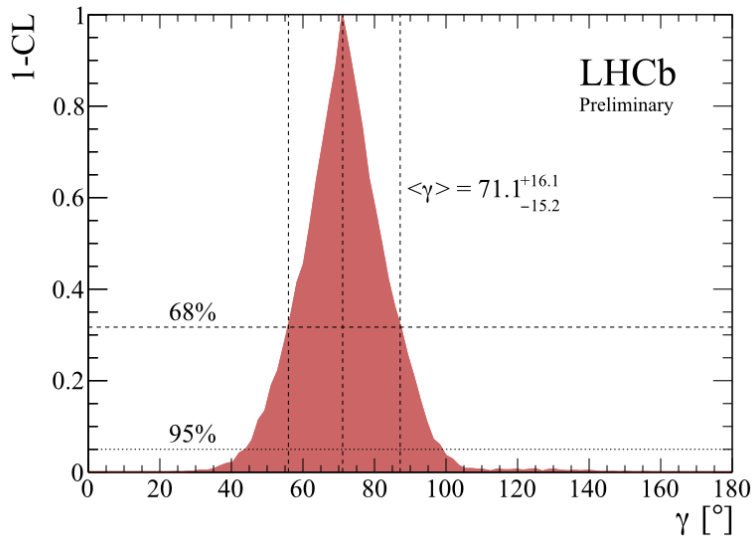


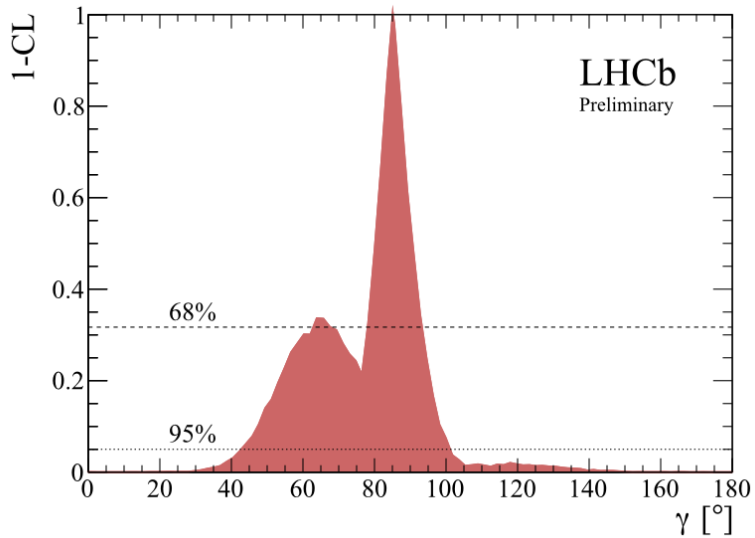
$D \to K_s KK$ final state

$$x_- = (0.0 \pm 4.3 \pm 1.5 \pm 0.6) \times 10^{-2} \qquad x_+ = (-10.3 \pm 4.5 \pm 1.8 \pm 1.4) \times 10^{-2}$$
$$y_- = (2.7 \pm 5.2 \pm 0.8 \pm 2.3) \times 10^{-2} \qquad y_+ = (-0.9 \pm 3.7 \pm 0.8 \pm 3.0) \times 10^{-2}$$

Gamma combination

- Gamma combination contains all mentioned measurements





Only $B \to DK$

$\gamma = (71.1^{+16.6}_{-15.7})^\circ$

Both $B \to DK$ and $B \to D\pi$

$\gamma \in [61.8, 67.8]^\circ$ or

$[77.9, 92.4]^\circ$ @68% CL ,

$\gamma \in [43.8, 101.5]^\circ$ @95% CL ,

Summary

- LHCb has made its first measurements of γ with $B^+ \to D^0 K^+$ and $B^+ \to D^0 \pi^+$ decays, using various methods (ADS, GLW, GGSZ) depending on the D^0 decay mode.
- Combination gives $\gamma = (71.1^{+16.6}_{-15.7})^\circ$ only for DK modes, which has similar precision to the Belle: $\gamma = (68^{+15}_{-14})^\circ$ and Babar: $\gamma = (69^{+17}_{-16})^\circ$ results
- This is only part of excellent LHCb results!
  LHCb also has first results on CP parameters in other modes: $B_d \to D^0(KK)K^{*0}$ or time-dependent measurement $B_s \to D_s K$.
- We work on new channels in the pipeline, e.g. $D_s K\pi\pi$, $D^0 K\pi\pi$.
- Stay tuned for more results in the future!
  LHCb collected $\approx 2.0 fb^{-1}$ at $8 TeV$ in 2012

Thank You!

γ world results

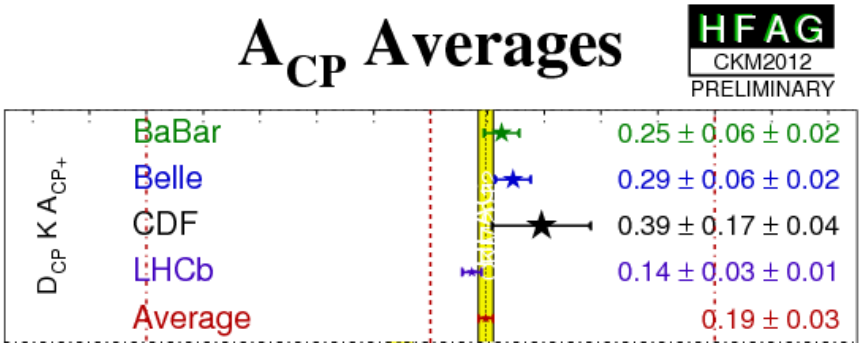
HFAG:

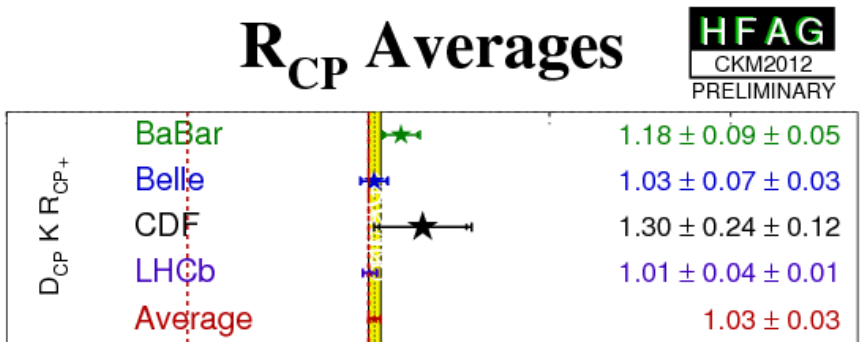
- *BaBar* use results from DK, D^*K and DK^* modes with GLW, ADS and GGSZ analyses
  $\gamma = (69^{+17}_{-16})^\circ$
- *Belle* use results from DK and D^*K modes with GLW, ADS and GGSZ analyses
  $\gamma = (68^{+15}_{-14})^\circ$
- LHCb use results from DK mode with GLW, ADS and GGSZ analyses
  $\gamma = (71.1^{+16.6}_{-15.7})^\circ$

UTFit: $\gamma = (76 \pm 10)^\circ$
CKMFitter: $\gamma = (66 \pm 12)^\circ$

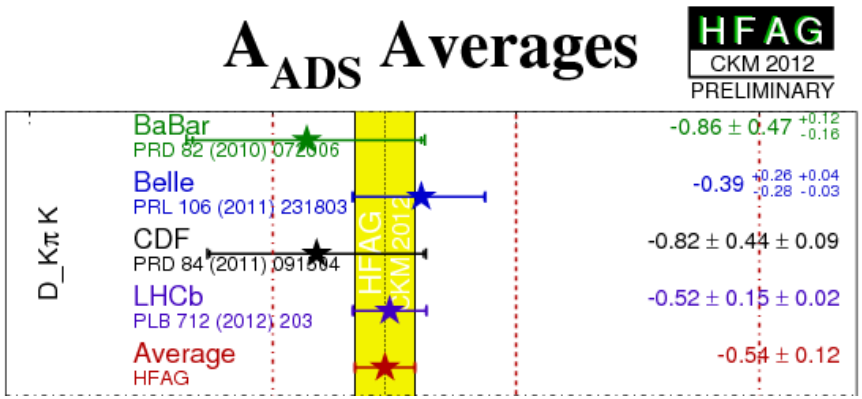
LHCb results significantly improve on the precision of previous B-Factory and TeVatron measurements.

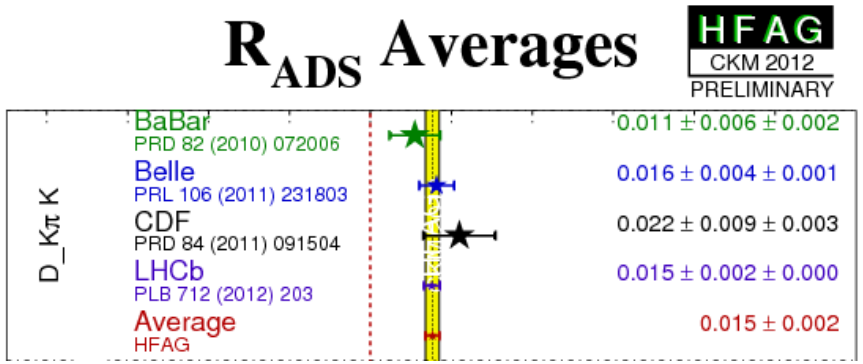
GLW results



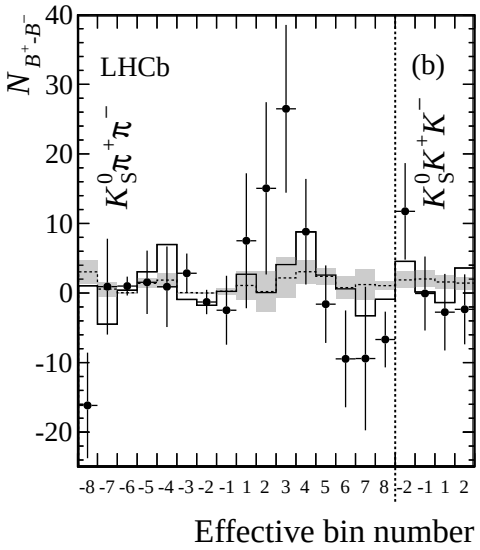


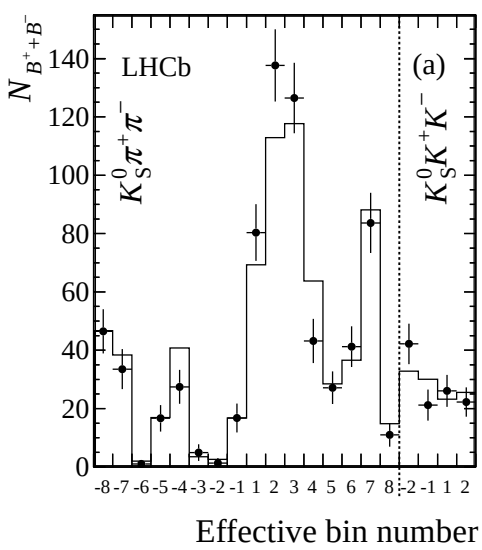
ADS results

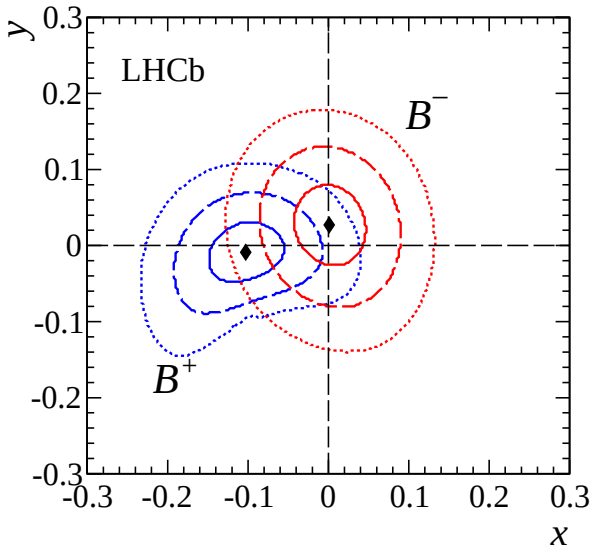


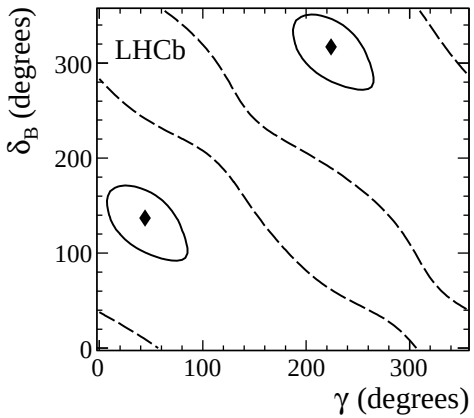


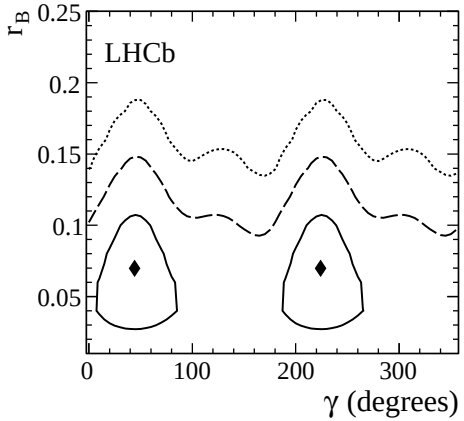
GGSZ

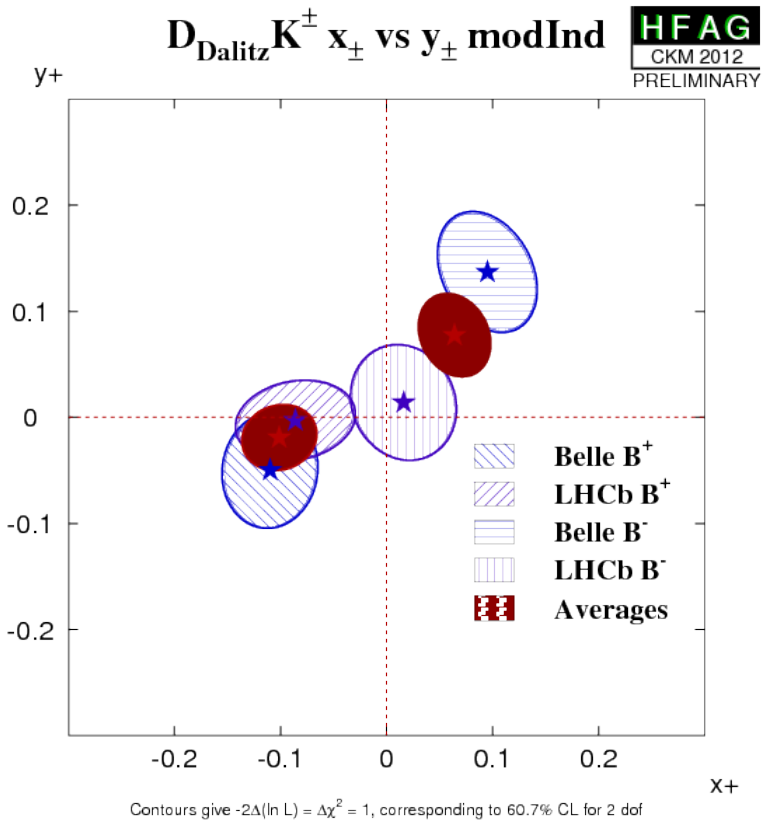

LHCb
(b)
$K^0_S\pi^+\pi^-$
$K^0_S K^+K^-$
$N_{B^+-B^-}$
Effective bin number


LHCb
(a)
$K^0_S\pi^+\pi^-$
$K^0_S K^+K^-$
$N_{B^++B^-}$
Effective bin number


LHCb
B^-
B^+
y
x


LHCb
δ_B (degrees)
γ (degrees)


LHCb
r_B
γ (degrees)

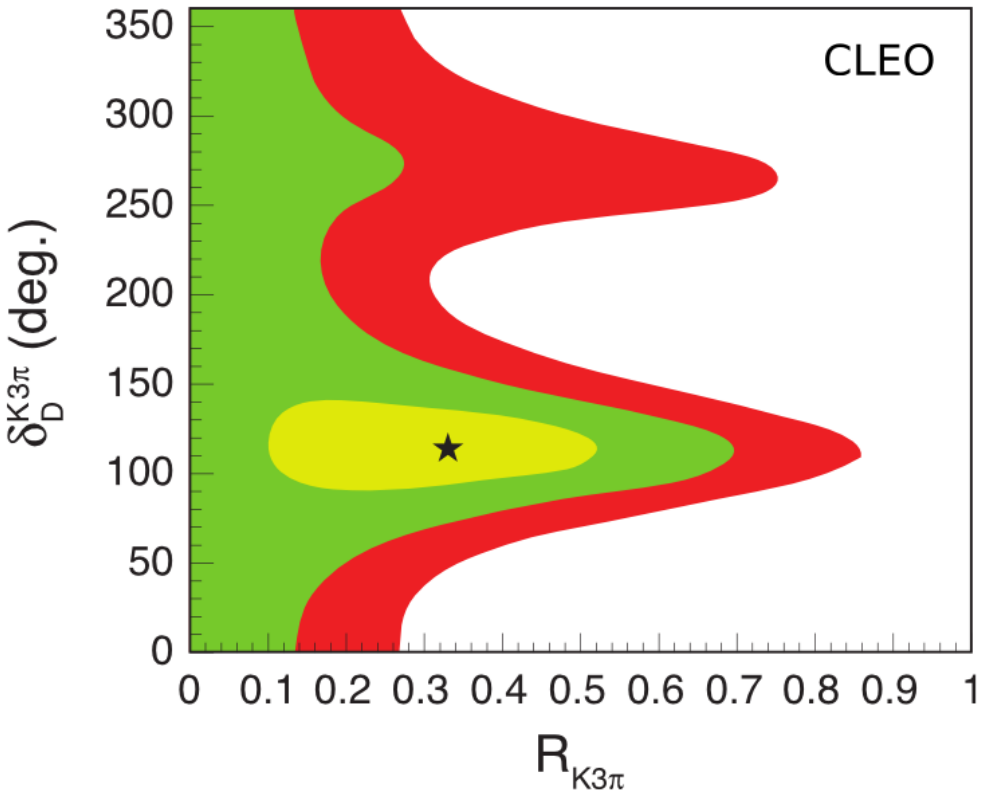


Belle (using $N(BB) = 772M$): $\gamma = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$

LHCb: $\gamma = (45^{+43}_{-38})^\circ$, ($r_B = 0.07 \pm 0.04$, $\delta_B = (137^{+35}_{-46})^\circ$)

(Despite the precision on x and y being similar to the B-Factories, the low measured value of r_B hurts the precision on γ).

CLEO input



CLEO likelihood for $\delta_D^{K3\pi}$ and $R_D^{K3\pi}$

$$\delta_D^{K3\pi} = 227^{+14}_{-17}$$

$$R_D^{K3\pi} = 0.84 \pm 0.07$$

from Phys.Rev. D80 (2009) 031105, arXiv:0903.4853

Strategy of fit

The strategy is to maximise, against a set of parameters $\vec{\alpha}$, a total likelihood built from the product of the probability density functions (PDFs) f_i of input experimental observables A_i,

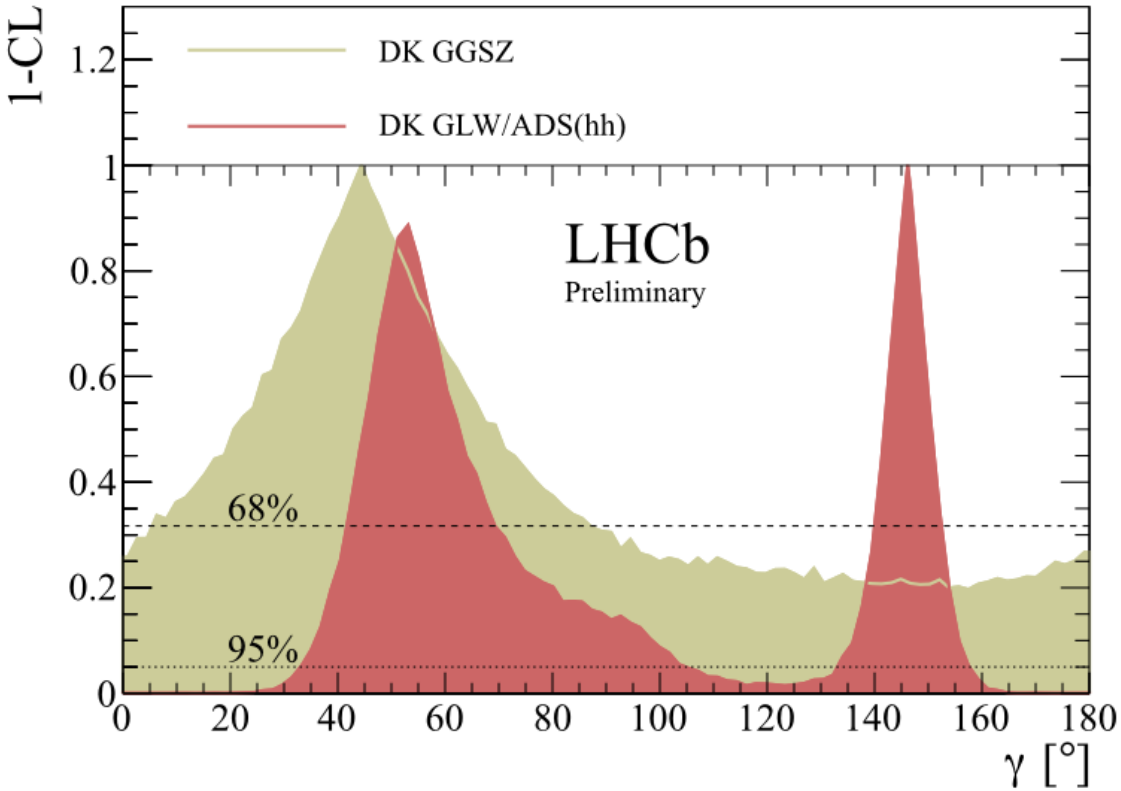
$$\mathcal{L}(\vec{\alpha}) = \prod_i f_i(\vec{A}_i^{\rm obs} | \vec{A}_i(\vec{\alpha}_i)) \ , \tag{1}$$

where the $\vec{A}_i^{\rm obs}$ are the measured central values of the observables and $\vec{A}_i(\vec{\alpha}_i)$ are the truth relations.

We define a χ^2-function as

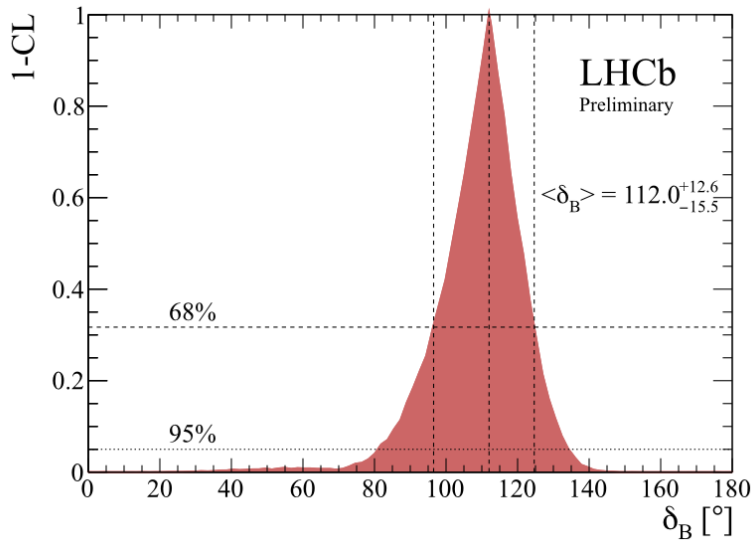
$$\chi^2(\vec{\alpha}) = -2 \ln \mathcal{L}(\vec{\alpha}). \tag{2}$$

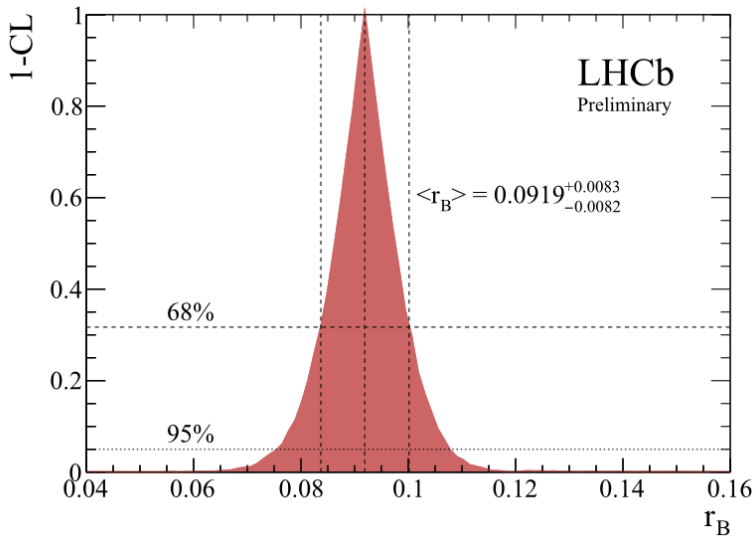
Result for γ



$1 - CL$ curves for γ for the DK parts of the two body GLW/ADS analyses (red) and for the GGSZ measurements (olive green).

r_B and δ_B for the DK only combination

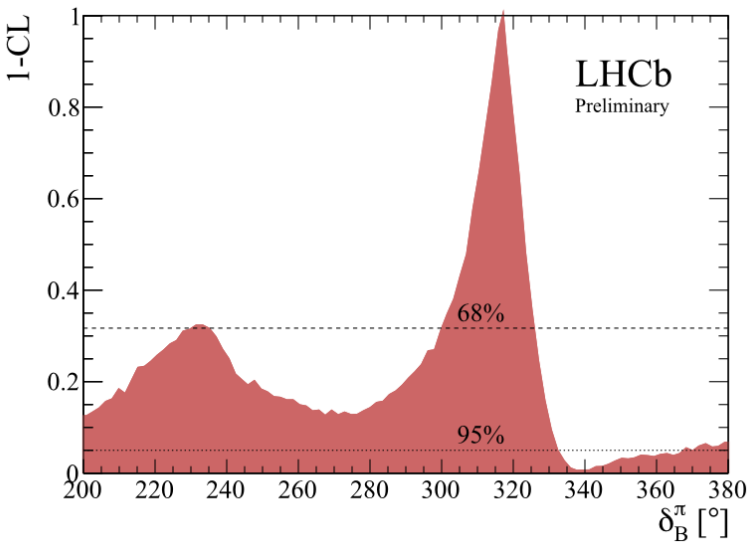


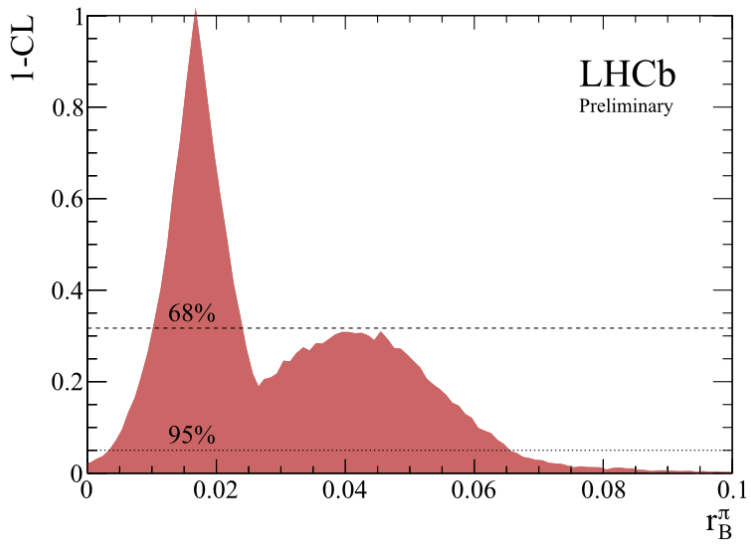


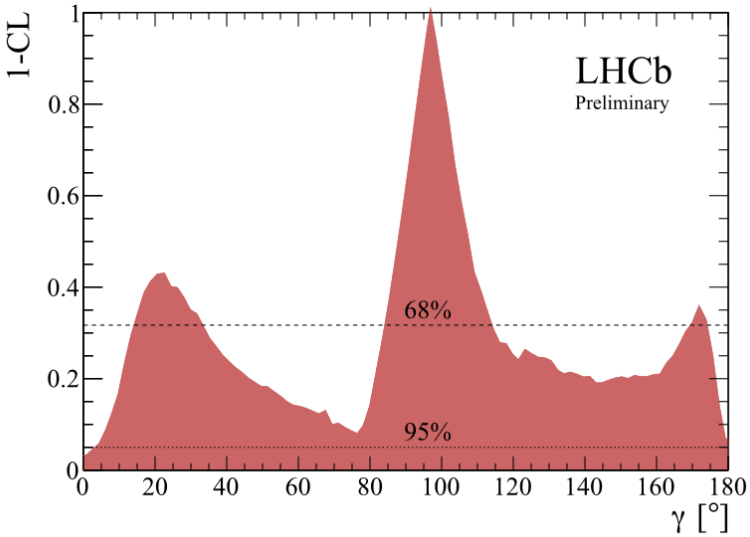
r_B	0.0919
68% CL	$[0.0837, 0.1002]$
95% CL	$[0.076, 0.108]$

δ_B	112.0°
68% CL	$[96.5, 124.6]^\circ$
95% CL	$[80.6, 134.3]^\circ$

γ, r_B and δ_B for the $D\pi$ only combination







γ	20.2°	96.9°	172.6°
68% CL	$[14.2, 33.1]^\circ$	$[84.4, 114.0]^\circ$	$[169.0, 173.7]^\circ$
95% CL	–	–	–
r_B	0.0168	0.0405	
68% CL	[0.0103, 0.0239]	–	
95% CL	$\leftarrow$ [0.004, 0.065] $\rightarrow$		
δ_B	232.3°	317.2°	
68% CL	$[229.2, 234.7]^\circ$	$[300.0, 326.1]^\circ$	
95% CL	$\leftarrow [187, 333]^\circ \rightarrow$		

2D plots

Profile likelihood contours, where green is 1σ,blue is 2σ and $-2lnL = (n\sigma)^2$. The markers correspond to local maxima of the likelihood.